MECHANICAL BEHAVIOUR OF THERMOPLASTIC STARCH/MONTMORILLONITE/ALUMINA TRIHYDRATE NANOCOMPOSITES

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Abstract

Thermoplastic starch (TPS) is a biodegradable biopolymer that has exhibited great prospects to replace conventional synthetic polymers in commercial applications. However, one of the most critical limitations of TPS is the lack of crucial mechanical properties. This study proposes the novel combination of *cassava* starch, montmorillonite nanoclay (MMT) and alumina trihydrate (ATH) in the form of a nanocomposite which is expected to demonstrate improved mechanical properties. The nanocomposites were processed through melt-extrusion in twin-screw extruder where loadings of MMT and ATH were varied between 1 to 6 wt% and 26 to 37 wt%, respectively. The mechanical properties were evaluated through tensile testing according to ASTM D882. The fractured surfaces of the specimens were evaluated using scanning electron microscopy (SEM) to further validate the mechanical properties of the nanocomposites. The melt viscosity and processability of the nanocomposites were also evaluated through melt flow index (MFI) testing according to ASTM D1238. Presence of MMT and ATH in TPS demonstrated increase in Young's modulus, maximum tensile stress and decrease in elongation at break up to 57.6 MPa, 5.1 MPa and 39.2%, respectively. In the presence of ATH, increase in loading of MMT continued to improve Young's modulus and maximum tensile stress while declining elongation at break. Without ATH, MMT was only capable of improving mechanical strength up to a loading of 3 wt% where adverse effects were observed when the loading was further increased to 6 wt%. Increase in loadings of both MMT and ATH, simultaneously were found to depreciate the MFI and thus, the processability of the nanocomposites.

Keywords: Thermoplastic starch, Montmorillonite, Alumina trihydrate, Nanocomposites, Mechanical properties.

Nomenclatures	
phr	Part per hundred parts of resin
Abbreviations	
ATH	Alumina Trihydrate
MMT	Montmorillonite
TPS	Thermoplastic Starch

1. Introduction

Plastics have become one of the most prominent commodities which are utilized in almost in every aspects of life. Various commercial fields have increasingly become highly dependent on plastics due to its versatile characteristics which enable it to be used in a wide range of applications. Plastics boasts vast number of applications ranging from modest role in packaging materials to complex engineering components including healthcare products, textiles, toys, electronics, biomedical uses, durable goods and many more [1-3].

Though plastics are highly regarded for its impacts towards technological advancements and uplifting of lifestyle, plastics have also acquired detrimental reputation over the years due to its negative effects on the environment. High durability of plastics is the main concern as it makes it invulnerable to microbial decomposition. Low density and high bulk of the plastics also turns out to be major drawbacks especially when landfill method for disposal is implemented as plastics tend to occupy large spaces [2]. The incineration or any other form of degradation of plastics, mainly derived from petroleum sources tend to contribute to net increase in greenhouse gases in the atmosphere despite many precautionary measures are in place to control the emissions [1]. In addition, many claims have been put forward that irresponsible disposal of plastic wastes in oceans results in accumulation of large quantities of plastics in oceans which in return affects the ecosystem and harms the aquatic life forms [2]. Fossil fuel has been the major and reliable feedstock for plastic manufacturing for the past 60 years [1]. Detrimental impacts of petroleum-derived plastics on the environment also establish the need for alternative feedstock for production of plastics.

The solution to the widespread and serious environmental concerns of conventional plastics as well as the overdependence on petroleum resources is identified to be the production of bio-based and biodegradable plastics derived from renewable resources. Biodegradable bioplastics from renewable resources are the perfect solution to the problems highlighted above as they offer renewability, biodegradability as well as low carbon footprint. The development of bioplastics is part of the initiatives employed under the sustainable and green technology development. Therefore, the challenge of this research is to produce a bioplastic with competitive performance compared to conventional plastics by incorporating blends of materials while retaining the renewability, and biodegradability. At the same time, the bioplastic is expected to maintain the processing methods and specifications of conventional plastics and thus, eliminating the need for major changes in unit processes in downstream plastic manufacturing.

Thermoplastic starch (TPS) or starch polymer is one of many bioplastics which has undergone extensive studies and researches recently due to its constructive prospect in the plastic industry. TPS is essentially gelatinized starch produced through application of sufficient heat and shear in the presence of plasticizers that results in disruption of starch granules due to the swelling of amorphous region [4-6]. Starch is a semi-crystalline polymer that does not melt in the conventional manner but instead, loses its crystallinity due to disruption of hydrogen bonds and consequently, disruption of starch granules under application of heat and shear [6]. Despite the promising potentials of TPS, it has some major flaws that impede it from being successfully commercialized. TPS is highly susceptible to retrogradation that is the effect of moisture absorption from the surroundings. This has caused many of the properties of TPS to be highly reliant on ambient humidity. TPS has very poor resistance to water and inferior mechanical strength relative to conventional synthetic polymers [3-7].

Nevertheless, the downsides of TPS can be improved by incorporating various nanofillers and other types of additives as previous researches have deduced that incorporation of foreign materials is the most effective approach in enhancing the properties of TPS [3]. In this research, the mechanical properties of TPS is attempted to be improved through incorporation of montmorillonite (MMT) nanoclay and alumina trihydrate (ATH). Nanoclays, also referred to as layered silicates, are the most commonly utilized and researched nanofillers as reinforcements in various polymers. Reinforcement using nanoclay is economically viable as it is highly effective in enhancing the tensile strength, modulus and other physical properties with minimum loadings ranging between 3 - 6 wt%, depending on the polymer type, processing technique and conditions [4, 7-14]. MMT is also highly favoured for usage in polymer industry due to environmentally benign nature, abundant availability and low cost [4, 7, 15]. On the other hand, ATH is an inorganic, non-toxic and environmentally friendly compound that is well-known and commonly employed flame retardant additive in many polymers. Although ATH is a significant flame retardant additive, it also greatly influences the mechanical strength of polymers. Therefore, effects of various loadings of MMT and ATH on the vital mechanical properties that are tensile strength, elastic modulus and elongation at break are investigated. Additionally, the melt viscosity and processability in industrial processing techniques are also investigated. The significance of each factor on the mechanical properties as well as interaction effects between the factors is studied by employing appropriate statistical analysis techniques.

2. Experimental

2.1. Materials

Native cassava starch powder was purchased from SCS Food Manufacturing Sdn. Bhd., Malaysia and employed in this research for preparation of TPS. The key motive behind this choice is that cassava starch or commonly denoted as tapioca starch is widely cultivated and commercialized in Malaysia contributing to its abundant availability. It was pointed out that the choice for the type of starch used in TPS production is greatly dependent on the regional influence of starch [5]. Glycerol was chosen to be the main plasticizer for TPS and was obtained from

Merck Sdn. Bhd., Malaysia. Untreated MMT (NANOLIN DK® nanoclay) was purchased by FCC®, Inc., China whereas ATH (Micral® 9400) was supplied by J.M. Huber Corporation, USA, with a purity of 99.5%. Laboratory formulated distilled water was used as additional plasticizer for TPS processing.

2.2. Design of experiments

A full factorial experimental design was employed with two factors - loadings of MMT and ATH. Each factor was assigned with three levels of loading where the levels are chosen based on literature reviews on previous publications in similar field. On top of that, the levels for each parameter were also chosen carefully to allow for clear observations with obvious variations of the results in experimental testing.

The levels for ATH loading was chosen to be in the range from 26 to 37 wt% [8, 9, 11, 16-18] whereas MMT loading was varied from 1 to 6 wt% [4, 7-11, 13, 14]. These ranges of loadings were repeatedly reported to have been effective in reinforcing polymers. Also, numerous test runs were conducted to validate the processability of the TPS with these loadings of additives. The full factorial experimental design with two factors with three levels each generated a total of nine experimental runs, i.e. $3^2 = 9$. In addition to this, three more control samples were included for better understanding of the effects of presence of MMT and ATH on the TPS. One of three control samples was composed of pure starch with no MMT and the other with low level of MMT and no ATH and the third with high level of MMT and no ATH. The composition of each formulation and corresponding levels of factors are shown in Table 1.

It has to be noted that each formulation sample is coded according to the level of loadings of MMT and ATH it contains. Each formulation code is followed with a prefix "F" followed by the level of MMT and correspondingly, the level of ATH. For example, formulation sample F2-3 denotes that the sample contains medium level of MMT and high level of ATH. Consequently, for control sample, sample formulation F3-0 denotes that the sample contains high level of MMT and no ATH.

Table 1. Formulations and corresponding levels of factors.

Factors	Formulations					
	F0-0	**F1-0**	**F3-0**	**F1-1**	**F1-2**	**F1-3**
MMT (wt%)	0	1	6	1	1	1
ATH (wt%)	0	0	0	26	30	37
Factors	Formulations					
	F2-1	**F2-2**	**F2-3**	**F3-1**	**F3-2**	**F3-3**
MMT (wt%)	3	3	3	6	6	6
ATH (wt%)	26	30	37	26	30	37

2.3. Preparation of TPS/MMT/ATH nanocomposites

100 g of starch was added along with 55 phr of glycerol and 15 phr of distilled water. The mixture was thoroughly stirred. MMT and ATH were subsequently

added in appropriate amounts according to the experimental design described in section 2.2 and as shown in Table 1. MMT was added and mixed to glycerol-swelled starch prior to addition of ATH. The mixture was melt-extruded in twin-screw extruder, SHJ-20 (Nanjing Giant Machinery Co., Ltd., China) with barrel temperatures set in the range of 155 °C to 170 °C from feeding point to the die and screw rotation speed within 300 to 360 rpm. For the control samples, that is the samples without ATH, the barrel temperatures were set in the range of 135 ^{0}C to 148 ^{0}C with similar screw speed as before. Each formulation was extruded with a basis of 100 g of starch each time and the steps were repeated multiple times to produce sufficient amount of samples for the sample characterizations and testing. The obtained extrudates were pelletized and stored in tightly sealed polyethylene zipper bags containing silica gels to prevent moisture absorption.

The pellets were removed from zipper bags and dried in oven at 40 ^{0}C for 30 minutes prior to moulding. The nanocomposite pellets were moulded using 25-ton hydraulic hot press, LS-22009-25 (Lotus Scientific Sdn. Bhd., Malaysia) before cut into dumbbell shape for tensile testing. The hot press temperature for the control samples without ATH was maintained at 145^{0}C while 165 ^{0}C was used for the rest of the samples. The standard mould dimension used was $150 \times 150 \times 1$ mm and approximately 60 g of samples were utilized for each mould. The samples were preheated for 5 minutes in the mould at the set hot press temperature before pressed for another 10 minutes. This was followed by air cooling for about 25 minutes before removing the samples from the mould. All the setting parameters for preparation of nanocomposites were identified through numerous test runs prior to the actual research experiments to ensure proper formations of nanocomposites without starch degradation or any form of flaws that could jeopardize the test results in the research.

2.4. Methods

Tensile tests were performed on each specimen according to the ASTM D882 on Tensile Tester Machine Series 5582 (Instron®, USA) with elongation rate set at 50 mm/min. The maximum tensile stress, Young's modulus and maximum elongation at break were recorded for each specimen.

The fractured surfaces of specimens were sputter coated with Au/Pd using Emitech© SC7620 Sputter Coater (Quorum Technologies, UK) and examined through scanning electron microscope (SEM), VP-SEM S-3400N (Hitachi, Ltd., Japan). The images were taken at 1000 times magnification at various locations along the fractured point.

Melt flow index (MFI) testing was carried out according to ASTM D1238 in Melt Flow Indexer, D4002HV (Dynisco Plastics, USA) using the pelletized extruded samples. Procedure A of ASTM D1238 was employed where the extrudates were cut at timed intervals using test load of 2060 g and the average mass of extrudates were recorded. The melting temperature was set at 145 ^{0}C for the control samples without ATH and 165 ^{0}C for the rest of the samples. The melt viscosity and the flow resistance of the samples were evaluated in terms of MFI or simply the mass of samples extruded in 10 minutes at the set temperature.

3. Results and Discussion

3.1. Tensile testing

The tensile tests were performed on the same day the nanocomposite films were molded as to avoid moisture absorption and subsequent retrogradation during the storage period. Retrogradation is a common phenomenon in TPS that is difficult to control, even with all the precautionary steps to prevent moisture contact with the samples. The tensile tests were performed on all the formulations according to ASTM D882, "Standard Test Method for Tensile Properties of Thin Plastic Sheeting", using the product of Instron®, USA, that is specifically designed according to this standard. Three vital mechanical properties were evaluated from this test - Young's modulus, maximum tensile stress and elongation at break.
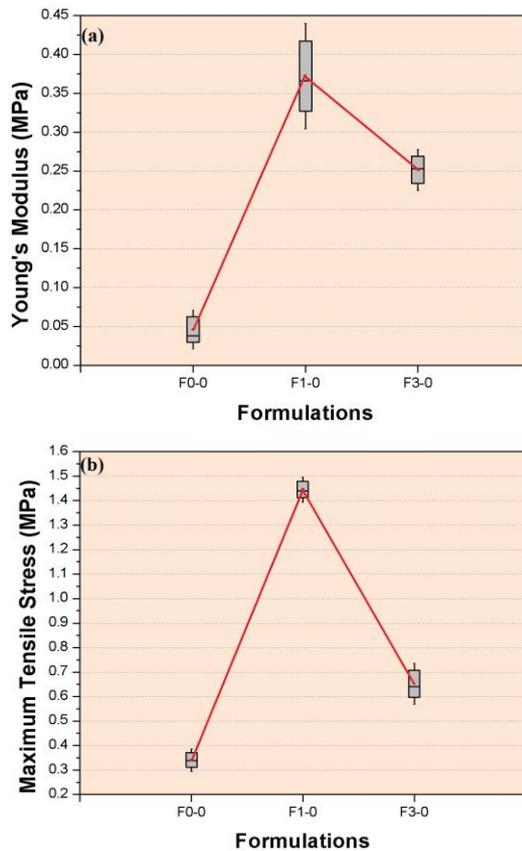
The Young's modulus, maximum tensile stress and elongation at break are tabulated in graphical form with boxplots indicating the standard deviations of the data for various formulations in Figs. 1 and 2. It was clearly evident from the figures that control samples without any ATH exhibited way lower Young's modulus compared to other formulations with ATH. In fact, the difference was so large, where the Young's modulus of formulations with ATH laid in the range between 3.9 MPa and 57.6 MPa while the control samples demonstrated Young's modulus in the range between 0.046 MPa to 0.37 MPa. Hence, it can be clearly inferred that the effect of presence of ATH in the nanocomposites was highly prominent where it was capable of increasing the Young's modulus by more than 1000 times with loading in the range of 26 wt% to 37 wt%. The effect of increase in ATH loading on the Young's modulus was most significant when 6 wt% MMT was incorporated, where there was a sudden upsurge from formulation F3-1 to F3-3. However, the effect of increase in ATH loading was not noteworthy when lower MMT loading was involved. In fact, a considerable depression was observed when ATH loading was increased from 26 wt% to 30 wt% while retaining MMT loading at 1 wt%. Apart from that, the effect of addition of MMT was also evident from results tabulated in Fig. 1(a), where addition of MMT up to 1 wt% increased the Young's modulus but deteriorated when the MMT loading was further increased to 6 wt%.

The trend in maximum tensile stress of the formulations was very much alike Young's modulus as previously observed. Similar to that of Young's modulus, the maximum tensile stress exhibited by control samples were many times smaller than the other formulations with ATH indicating that presence of ATH have again demonstrated substantial effect on the mechanical properties of the nanocomposites. The effect of increase in loading of ATH was made even more prominent when 6 wt% of MMT was retained in the nanocomposites as evident from sudden increase in maximum tensile stress from formulation F3-1 to F3-3. Likewise, the maximum tensile stress also tend to increase when loading of ATH was increased while 3 wt% of MMT was retained, but the increase was not as significant as when the MMT loading was at 6 wt%. Conversely, a significant depression in maximum tensile stress was observed when loading of ATH was increased from 26 wt% to 30 wt% while maintaining constant MMT loading at 1 wt%. Also, the addition of MMT increased the maximum tensile stress up to loading of 1 wt% and declined when the loading was further increased to 6 wt%.

As expressed in Fig. 2(c), the highest elongation at break was achieved by the pure TPS with no MMT and ATH, that is, formulation F0-0. Generally, the

elongation at break gradually declined with increase in loading of MMT and ATH. As anticipated, the lowest elongation at break was exhibited by sample with the highest loading of MMT and ATH, that is, formulation F3-3. Again, formulation F1-2 displayed an unusual behaviour where the elongation at break increased when the loading of ATH is increased from 26 wt% to 30 wt%.

As it can be seen from collective tabulations of results above, the tensile testing on sample F0-0 yielded Young's modulus, maximum tensile stress and elongation at break with values of 0.046 MPa, 0.34 MPa and 535.7% in average, respectively. Conversely, the mechanical properties of melt-extruded pure TPS with 20 to 25 wt% of glycerol content are reported to be in the range of 5.43 to 6.79 MPa and 37.21 to 74.49% for maximum tensile stress and elongation at break, respectively [19]. As compared to findings by Moscicki et al. [19], the difference is mainly attributed to the high glycerol and water content that is employed for all the formulations in this research. In fact, 33 wt% of glycerol and 9 wt% of water was used in this experimental study to improve the processability of the nanocomposites in extruder in the presence of ATH.

**Fig. 1. Young's modulus (a) and
maximum tensile stress (b) of control samples.**
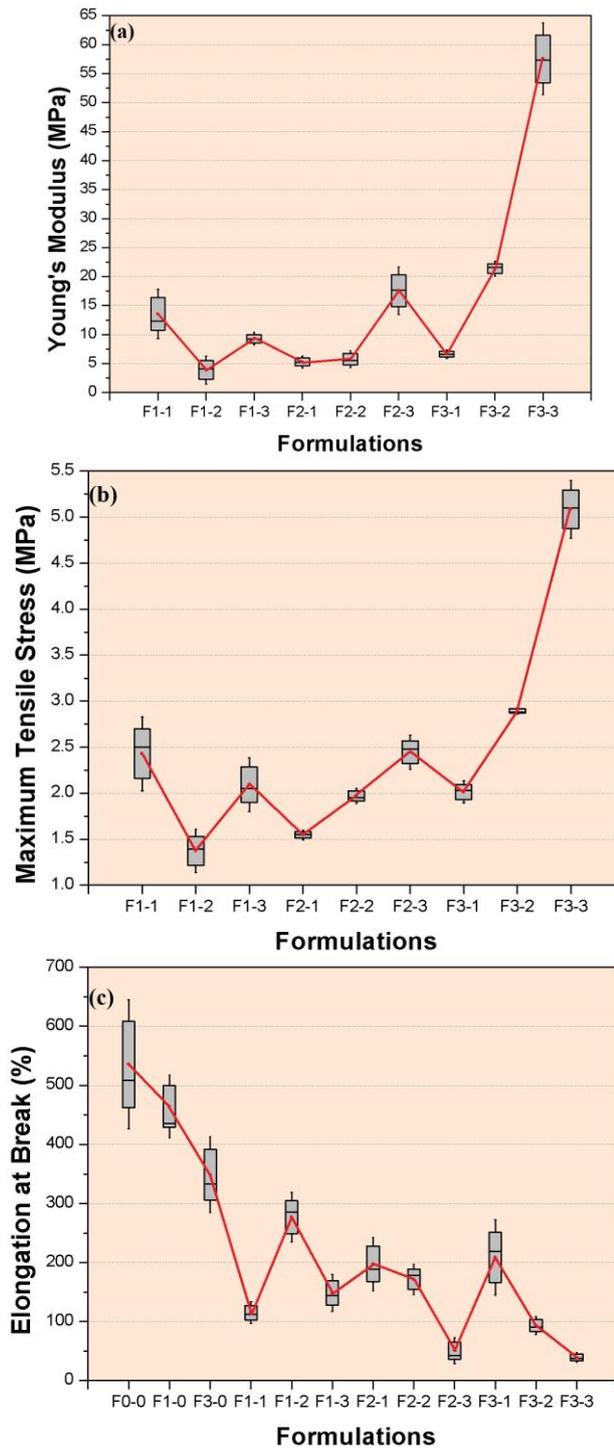
**Fig. 2. Young's modulus (a), maximum tensile stress (b)
and elongation at break (c) of various formulations.**

Apart from that, the results obtained from this research study are somewhat in accordance to the previously published works. The increase in MMT was found to increase the mechanical properties to a certain extent after which it deteriorates when the maximum threshold loading is exceeded. Loading of MMT up to 5 wt% is reported to have improved the Young's modulus and maximum tensile stress of various polymer nanocomposites [4, 7, 11]. Similarly, in this research, the addition of MMT have evidently improved the Young's modulus and maximum tensile stress up to loading of 3 wt% and declined when the loading was further increased to 6 wt%. Therefore, it could be inferred that the threshold for MMT loading lies somewhere in between 3 wt% and 6 wt%. The considerable decrease in elongation at break with increasing MMT loading is also reported by numerous previous publications [4, 7, 12, 14]. Also, ATH is repeatedly reported to have increased the Young's modulus and maximum tensile stress while decreasing elongation at break significantly, especially at high loadings [8, 11, 16, 17]. Similar trend was observed from the results obtained from this research study when loading of ATH is increased in the nanocomposites.

Table 2 shows the comparison of mechanical properties obtained in this research with various published mechanical properties of glycerol-plasticized TPS/MMT nanocomposites. It is obvious that the mechanical properties of the nanocomposites registered in this research study are inferior to the mechanical properties published by other researchers, even by only incorporating MMT as filler. The main reason for the nanocomposites in this research to possess such poor mechanical properties is deduced to be the high plasticizer content that was used for the nanocomposites processing. High plasticizers content was employed in this research in order to improve the processability of the nanocomposites in the extruder, despite knowing that it will compromise the mechanical properties. While all the listed researches in Table 2 employed plasticizers in the range of 23 wt% to 33 wt%, this research employed an astounding amount of total plasticizer which sums up to 42 wt%, relative to base starch polymer.

Table 2. Comparison of mechanical properties of TPS/MMT/ATH nanocomposites of this research with various published results.

Author	Filler(s)/Additive(s)	Young's modulus (MPa)	Maximum tensile stress (MPa)	Elongation at break (%)
Current research study	MMT: 1 - 6 wt% ATH: 26 - 37 wt%	3.9 - 57.6	1.37 - 5.1	39.2 - 276.8
Cyras et al. [4]	MMT: 0 - 5 wt%	29.8 - 195.6	3.1 - 5.2	37.6 - 62.6
Park et al. [7]	MMT: 0 - 5 wt%	N/A	2.14 - 3.32	34.9 - 57.2
Huang et al. [20]	MMT: 0 - 30 wt%	38.15 - 206.74	5.51 - 27.34	17.82 - 85.32
Muller et al. [21]	MMT: 0 - 5 wt%	16 - 90	0.96 - 2.22	63 - 76

Plasticizers, in general, possess the ability to form hydrogen bonds with starch molecules and weaken the interactions between the starch molecules in the process. This allows the starch molecules to slide past each other, resulting in decrease Young's modulus and maximum tensile stress and corresponding increase in elongation at break [22]. It is also reported by Ma et al. (2005) that excessive plasticizers will not be bounded with TPS and tends to be volatilized when heated during processing. In general, plasticizer content below 40 wt% found to be completely bounded with TPS and plasticizer content at 30 wt% is reported to have fairly good mechanical properties [22].

3.2. Scanning electron microscopy

The fractured surface of the specimens after it have undergone tensile testing were subjected to SEM tests. Essentially, SEM enabled examination of surface morphology of the nanocomposites at close proximity, at thousands of times of magnification. SEM tests also allowed inspection on the nature of fracture the specimen has endured during the tensile testing. The plasticity or brittleness of the specimen could be easily noticed via SEM. On top of that, SEM tests were also able to pick up on uneven distribution of components along the base polymer matrix [23]. SEM tests are vital to further support, validate and explain the mechanical behaviour exhibited by nanocomposites in tensile tests. The SEM images captured at 1000 times magnification are presented in Fig. 3 and 4.

As evident from SEM micrographs, formulation F0-0 showed smooth surface morphology. This is well anticipated as it does not contain any filler and is only composed of gelatinized starch. The specimen also indicated multiple fracture points spread across the surface indicating uniform stress distribution and consequent significant plastic deformation. However, small and shallow cavities along the surface are also observed. It was inferred that it could have been caused by evaporation of water and/or glycerol during the storage period prior to testing. It is very well-known that characteristics of pure TPS are highly dependent on ambient relative humidity as it tends to have very poor water resistivity [3-7]. The formation of cavities could also be the result of volatilization of unbound, excess plasticizers in TPS [22]. Although high glycerol and water content was necessary for formulations with high ATH content to promote processability in extruder, it was probably too excess and redundant for pure TPS. Formulation F0-0 also showed significant plastic deformation with clear elongation and stretching of polymer matrix.

Likewise, formulations F1-0 and F3-0 also demonstrated very smooth surface morphologies indicating homogeneity between the polymer matrix and MMT. MMT was dispersed uniformly across the starch polymer matrix. Both the samples presented extensive plastic deformation as indicated by multiple stress lines. Nevertheless, sample F3-0 is understood to be slightly lacking in elongation compared to F1-0 as the stretching and pulling of the materials towards the fracture point is not as significant. As for the rest of the formulations with ATH, poor homogeneity of components was evident, where large grains of unprocessed starch molecules were clearly visible in SEM images of samples F1-1 to F3-3. Native granular starch molecules were not completely destroyed and thus, failed to form a continuous phase. Smaller aggregates seen in the images could be attributed to agglomeration of MMT and/or ATH molecules. In overall, there is

poor dispersion of molecules throughout the entire polymer matrices caused by inadequate bonding between the components. This could have served as one of many reasons the formulations registered poor mechanical properties compared to other published researches. The lack of dispersion and bonding of components in polymer matrix was most prominent in formulation F1-2. This is found to be in direct conformation with the tensile testing results where the formulation F1-2 had scored the lowest Young's modulus and maximum tensile stress with corresponding highest elongation at break. Chemical or irradiation cross-linking could be employed to improve the facial interaction between the components as well as with the polymer matrices which would improve the dispersion and correspondingly, the mechanical properties of the nanocomposites [24, 25].
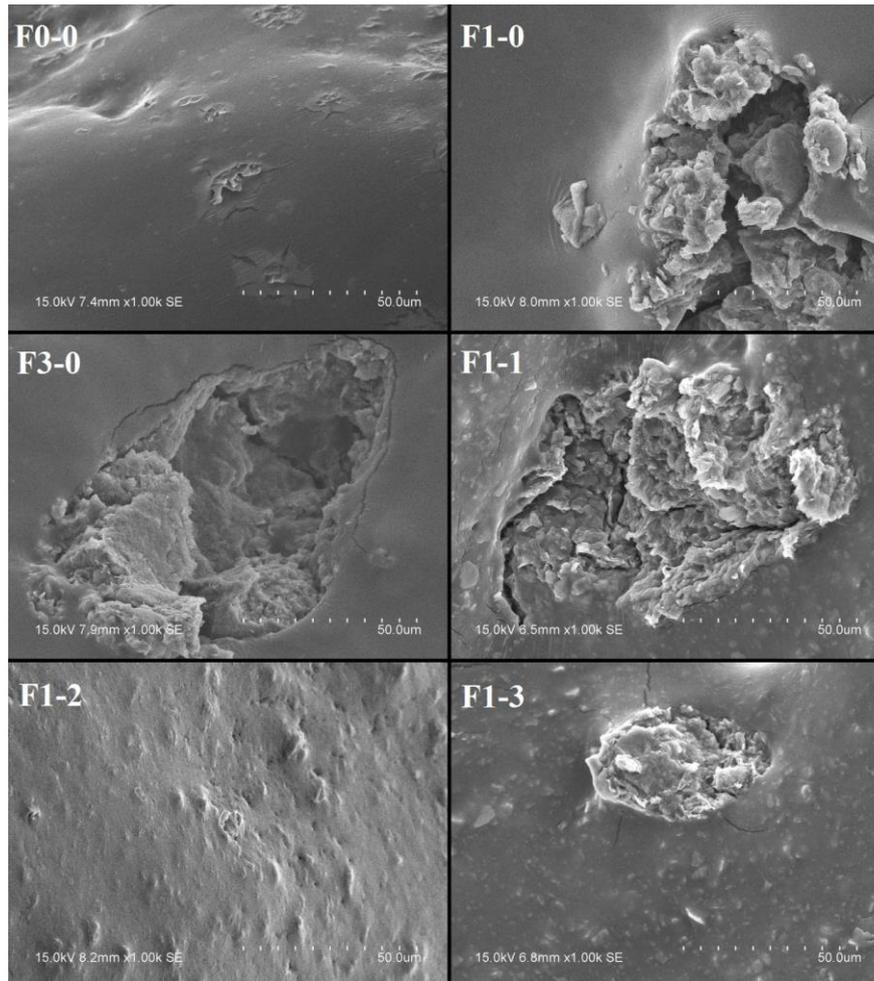
Fig. 3. SEM micrographs of fractured surfaces of various specimens at 1000 times magnifications: F0-0 to F1-3.
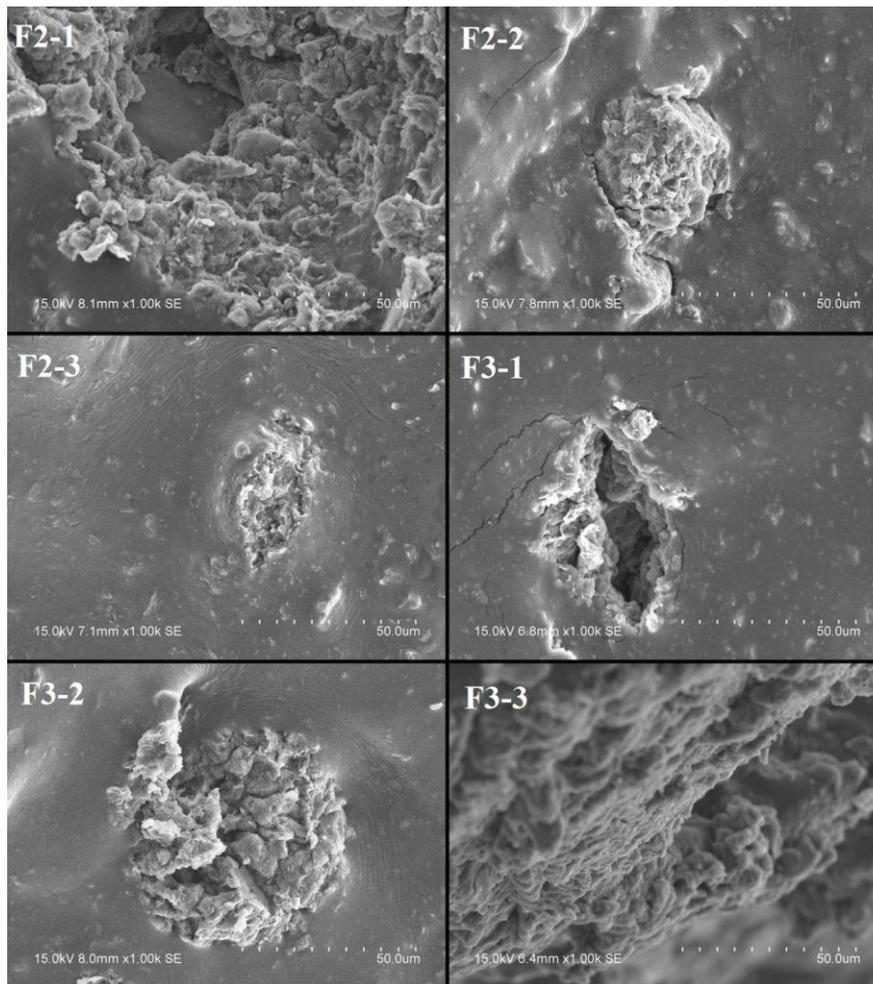
**Fig. 4 SEM micrographs of fractured surfaces of various
specimens at 1000 times magnifications: F2-1 to F3-3.**

Formulations F1-3 to F3-2 showed considerable plastic elongations as indicated by stretched surfaces, stress lines and protruding or caving in fracture points. Conversely, formulation F3-3 displayed very little or almost insignificant deformation before fracture as seen from the SEM image. This validates the tensile testing results where formulation F3-3 exhibited the lowest elongation at break compared to the rest of the formulations. Stretching of polymer matrices in formulations F1-3, F2-2 and F3-1 caused visible cracks to form. If observed closely, smaller creases and crazing can also be observed in these three formulations. Formation of cracks, creases and crazing in could have been the result of progressive recrystallization which is common in glycerol and water plasticized TPS [26]. Substantial recrystallization in glycerol and water plasticized TPS is widely reported, especially over prolonged storage period where it proves to be detrimental to mechanical strength of the polymer [27-29]. Ma and Yu [28] also explained that recrystallization is dependent on the ability to form hydrogen bond between the plasticizers and starch molecules where, the stronger the bond, the less

likely it is for the TPS to recrystallize during prolonged storage. Chen and Evans [26] suggested replacing of commonly used plasticizers like glycerol and water to other plasticizers that tend to promote stronger hydrogen bonds to reduce the extent of recrystallization during storage. Ammonium-treated hectorite as plasticizer in TPS is reported to have managed to successfully inhibit recrystallization that results in embrittlement and cracks [26]. Therefore, any plasticizers containing NH^{4+} and or NH^{2-} ions could serve as optimum plasticizers for TPS.

3.3. Melt flow index

Essentially, melt flow index (MFI) testing characterizes the flow behaviour of the nanocomposites, providing information regarding the processability of nanocomposites in industries. MFI refers to the mass of extrudate that flows out of a standard die in 10 minutes at the set temperature and load. MFI is an inverse measure of melt viscosity of polymers, where higher the MFI, the lower the melt viscosity and thus, more polymers flows through the die at the set test conditions [30]. MFI can also provide with indication on the suitable processing techniques that should be employed for different polymers. For example, polymers with high MFI are most suitable to be processed by means of blow moulding or injection moulding while polymers with low MFI are best processed through extrusion process [31]. However, it should be noted that MFI only provides with a very crude and approximate assessment. Hence, MFI testing is mainly utilized for industrial application where it is used as a quality control to determine the quality and attributes of polymer before it is processed in the machineries.
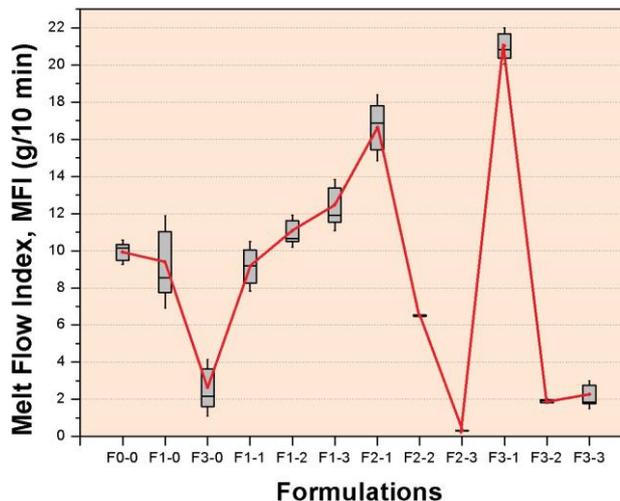

Fig. 5. MFI of various formulations.

4. Conclusions

Glycerol and water plasticized TPS/MMT/ATH nanocomposites with various loadings of MMT and ATH were successfully synthesized through extrusions in twin-screw extruder followed by hot pressing. In conclusion, both the presence of MMT and ATH greatly improved the mechanical strength of the nanocomposites:

- The Young's modulus and maximum tensile stress were increased to a maximum of 57.6 MPa and 5.1 MPa, respectively while the elongation at break is greatly diminished to 39.2%.
- In the absence of ATH, increase in loading of MMT continued to improve mechanical strength while declining elongation at break.
- When MMT was incorporated together with ATH, the mechanical strength was only improved with increasing loading of MMT up to 3 wt%.

The SEM micrographs also revealed that control samples without ATH exhibited homogenous dispersion over the starch polymer matrices. The rest of the samples with ATH present showed poor homogeneity as large grains of unprocessed native starch molecules and smaller aggregates of molecules suspected to be MMT and/or ATH were clearly visible. MFI tests revealed that increase in loading of MMT and ATH simultaneously increased the melt viscosity. However, the MFI was increased as the loading of ATH was increased while maintaining constant MMT loading at 1 wt%. It was deduced that such behaviour was the result of flame retarding characteristics of ATH that had progressively reduced the extent of starch degradation at high temperature.

Acknowledgement

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